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Return-flow assessment for irrigation command in the Palleru river basin using SWAT model

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Abstract:

Due to the ever-increasing demand for water resources, the pressure on their judicious utilization is also increasing. Besides being precious, water is also a very complex commodity. The dynamic nature of weather as well as the spatial variability of landmass contribute to the dynamic behaviour of the response of the watersheds to the natural and artificial inputs of water. This requirement has led to the formulation of continuous, distributed parameter, water balance simulation models capable of providing insight into the distribution and utilization of water in a watershed. Since they mimic the natural processes prevalent in the area, they are capable of providing many answers that are normally not easily available otherwise. In the present paper one such situation has been tackled using the SWAT (Soil and Water Assessment Tool) model. The target question was to assess the return flow on account of introducing canal irrigation in a basin (Palleru river basin in the southern state of Andhra Pradesh, India). Since the return flow is dependent on many aspects such as soil characteristics, method of irrigation, etc., it is not appropriate to put a rule-of-thumb value on such quantities. Through modelling, the return flow has been assessed and validated. The temporal variation of such return flows has also been captured. The virgin flows from the basin, before the manmade changes in construction of reservoir and importing water for irrigation were introduced, were also computed as per the requirement of the department. In fact this has been an exercise in demonstrating the usefulness of creating such a base framework capable of helping water managers in planning and management of this very vital resource.

KEY WORDS return flow assessment; water balance; simulation models; SWAT; water resource management; irrigation command

INTRODUCTION

The ever-increasing demand for water resources has required water resources development to be undertaken in every part of the world. One very common form of such development has been in terms of the creation of irrigation projects. Proper assessment of such manmade changes is essential for efficient utilization of the created potential as well as the sustainability of such development. It is understandable that such manmade changes shall influence the water balance of the local river system. However, it is very difficult to quantify such changes. The process-based water balance models are better placed to perform such analyses. The present study is a pilot case study to demonstrate such capability of a conceptual model, namely the SWAT (Soil and Water Assessment Tool) model.

The specific objectives of the study have been to (a) quantify the return-flow coming back to the river system on account of the development of an irrigation project, and (b) estimate the runoff yield of the basin when no manmade interference occurred (virgin yield) in the Palleru river basin of the Krishna river system in the state of Andhra Pradesh, India. This opportunity was also utilized to demonstrate the usefulness of

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the water balance modelling framework for integrated water resources management, so that the same can be adopted by the state government.

THE STUDY AREA

Some salient features of the Palleru sub-basin (NWDA, 1991) are given below.

The Palleru sub-basin lies between latitude 16°39′ and 17°15′N and longitude 79°17′ and 80°09′E, comprising the catchment area of the river from its source to its outfall in the River Krishna.

The length of the Palleru River from its source to its outfall is 152 km. The sub-basin has the shape of a fern leaf. The catchment area of the Palleru sub-basin lies entirely in the state of Andhra Pradesh. Part of Khammam, Warangal, Nalgonda and Krishna districts fall in this sub-basin.

Climate

The climate is characterized by hot summers and mild winters. There are two India Meteorological Department (IMD) observatories at Khammam and Hanumakonda (Warangal district), located on the periphery of the sub-basin.

There are 12 rain gauge stations in and around the basin, out of which rainfall data for seven stations were available and are used in the current study. The daily rainfall data for these are available for the period from 1963 to 1994. The basin experiences predominantly southwest monsoon (June to November). The temperature data is recorded at Khammam and Hanumakonda.

Soil and land use

The soils of the Palleru sub-basin are broadly grouped as red earths with loamy subsoils and black cotton soils. Red soils with loamy subsoils, known locally as red chalkas, are the predominant group in this sub-basin. Land use consists of agriculture, forest, urban, barren and rocky areas. Major crops grown are paddy (rice), jowar (sorghum), groundnut and pulses.

Runoff measurements and irrigation system

There are seven tributaries joining the Palleru River, five on the right side and two on the left side. There is one gauge and discharge site maintained by the Central Water Commission (CWC), a central government agency, at Palleru Bridge, slightly upstream of the confluence of the Palleru River with the Krishna River.

The Nagarjuna Sagar Left Bank (NSLB) canal cuts across the Palleru basin almost through the middle. The NSLB canal imports water into the Palleru basin. A part of the NSLB canal water is distributed in the Palleru basin through a number of distributary canals, whereas another part is also used to fill up the Palleru reservoir situated inside the basin on the Palleru River. The downstream portion of the NSLB canal also carries some water beyond the Palleru basin. This arrangement renders the overall system a highly complex one.

Brief description of the SWAT model

The SWAT model, developed by the Agricultural Research Service (Arnold *et al*., 1996), simulates the hydrologic cycle as well as the cycles of plant and root growth, harvest and decay in daily time steps. Routines are also included for simulating the detachment of sediments from the watersheds and their transport through the river systems. The SWAT model is designed to route water and sediments from individual watersheds, through the major river basin systems. It can incorporate the tanks and reservoirs off-stream as well as on-stream. The agricultural areas can be irrigated using diversions from within the sub-basin or from outside the sub-basin. The major advantage of the model is that, unlike other conventional conceptual simulation models, it does not require much calibration.

The model can be used for the assessment of existing and anticipated water uses and water shortages. The model provides a complete account of the quantities of water that: are supplied to the land by precipitation; enter the streams as surface runoff; are used and returned to the atmosphere by natural vegetation, agricultural crops and evaporation; and percolate through the root zone and partly return as groundwater contribution.

The SWAT model has been interfaced with many platforms, one of the more versatile being its interface with the ArcView GIS system (AVSWAT). The AVSWAT (User's Guide, 1999) has been used in the present study for pre- and post-processing of input/output data for SWAT.

Pre-processing of data from the Palleru basin for SWAT runs

A toposheet with 1 : 250 000 scale has been used to create coverages of contours, detailed drainage networks, manually delineated subwatershed boundaries, canal networks, etc. Soil coverage was prepared using the district boundary map. The characteristics of the typical soils are given in Table I.

Similarly, land use coverage was prepared by attaching the land use to the village boundaries. This is coarse information, which has been taken as input for the first level exercise.

The SWAT model requires the generation of long-term weather statistics to be used to simulate some of the parameters for evapotranspiration. These statistics are generated using a weather generator module. Fifteen years of data has been used to generate these statistics. Statistics for one of the stations (Khammam) are provided in Table II. These statistics will also be useful for generation of weather data in case future scenarios need to be investigated on the basin. However, in the present simulation the actual rainfall data has been used for the simulation runs.

In addition to the two weather stations, seven rain gauge locations have been used and are shown in Figure 1. These stations are associated with sub-basins for the SWAT simulation on the basis of their close proximity with respect to the centroid of the sub-basins.

DEM generation

The DEM (digital elevation model) of the study area has been generated using contours taken from a 1 : 250 000 scale topographic map of the study area. The cell resolution of 200 m × 200 m has been used to generate a drainage pattern and to derive physical characteristics of the watersheds.

Table I. Typical soil characteristics of red chalkas soil

Depth (mm)	600·00	1500·00
Bulk density (t/m^3)	1·46	1·56
Available water capacity (m/m)	0·17	0·17
Saturated conductivity (mm/h)	26·00	26·00
Organic carbon content (%)	0·23	0·23
Clay content (%)	15·80	15·80
Silt content (%)	10·20	10·20
Sand content (%)	74·00	74·00
Rock fragments (%)	0·00	0·00
Moist soil albedo	0·02	0·02
Dry soil albedo	0·04	0·04
USLE erosion K-factor	0·32	0·32

Table II. Long-term weather statistics for Khammam weather station

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
28·25	30·91	35·19	37·92	39·19	36·22	32·18	31·22	31·75	31·37	29·89	28·60	TMP_MX
16·32	18·00	22·57	25·20	26·31	26·39	24·44	23·82	23·93	22·03	19·44	17·13	TMP_MN
0·26	0·28	0·12	0·13	0·20	0·14	0·15	0·15	0·16	0·16	0·09	0·11	TMP_CV
500·00	560·00	620·00	680·00	640·00	500·00	450·00	470·00	495·00	520·00	500·00	475·00	SOLAR_AV
7·00	8·00	12·00	6·00	22·40	44·40	35·00	9·00	15·00	29·60	25·00	1·50	RAIN_HHMX
0·02	0·01	0·04	0·05	0·10	0·28	0·47	0·39	0·30	0·14	0·05	0·02	PR_W1
0·42	0·33	0·16	0·16	0·27	0·55	0·64	0·69	0·59	0·64	0·48	0·20	PR_W2
0·80	0·40	1·27	1·67	3·73	11·40	17·40	17·13	12·60	8·60	2·80	0·67	PCPD
0·18	0·07	0·37	0·29	1·80	3·90	8·20	7·19	5·04	4·26	0·92	0·09	PCP_STAT1
6·80	5·55	10·49	5·65	18·10	12·64	18·76	17·66	17·77	25·25	13·13	3·09	PCP_STAT2
1·20	0·86	1·52	1·31	1·78	1·92	2·00	2·36	3·10	3·69	1·99	0·43	PCP_STAT3
16·35	16·61	18·68	19·91	20·52	21·85	23·09	23·59	23·91	21·87	18·38	16·46	DEWPT
0·73	0·68	0·69	0·65	0·58	0·64	0·76	0·78	0·78	0·75	0·71	0·72	WND_AV

TMP_MX: Average maximum air temperature for month (°C). TMP_MN: Average minimum air temperature for month (°C). TMP_CV: Coefficient of variation for the average temperature for month (°C/°C). SOLAR_AV: Average daily solar radiation for month (langleys/day). RAIN_HHMX: Maximum half-hour rainfall in entire period of record for month (mm). PR_W1: Probability of a wet day following a dry day in month. PR_W2: Probability of a wet day following a wet day in month. PCPD: Average number of days of precipitation in month. PCP_STAT1: Average daily precipitation in month (mm/day). PCP_STAT2: Standard deviation for daily precipitation in month (mm/day). PCP_STAT3: Skew coefficient for daily precipitation in month. DEWPT: Average dew point temperature in month (°C). WND_AV: Average wind speed in month (m/s).

Watershed (sub-basin) delineation

A threshold value of 6500 ha has been used to generate the stream network, which primarily controls the density of the stream network and consequently the number of sub-basins the basin gets divided into. The drainage network of the study area is shown in Figure 1.

The confluence of the Palleru River with the Krishna River has been selected as the outflow point. The Palleru basin has been divided into 22 sub-basins with respect to the selected threshold. The sub-basins are shown with their numbers in Figure 1.

Reservoir and imports (from the NSLB canal)

The Pellaru reservoir located in sub-basin 22 (Figure 1) acts as a control reservoir in conjunction with the NSLB canal. The imports from the NSLB canal get bifurcated into many distributaries, which transport the irrigation water to various sub-basins. These distributaries serve four sub-basins, i.e., sub-basins 12, 13, 14 and 15. There has been another release directly from the Palleru reservoir for irrigation purposes. This release from the reservoir into the Palair channel is discharged to sub-basin 11.

Soil layer

A soil map has been prepared by attaching the district-wise soil characteristics data. The characteristics of the typical soils are given in Table I.

HRU definition/distribution

The hydrologic response units (HRUs) are composed by overlying the land use and soil type layers in each of the topographically defined sub-basins. A 10%/10% land use/soil distribution has been used to identify the HRUs. The 22 topographically defined sub-basins have been divided into 62 HRUs with respect to this criterion. Model inputs including weather, soils, groundwater and management are required for each HRU. Soil water balance, crop growth, nutrient cycling, management, etc. are simulated for each HRU.

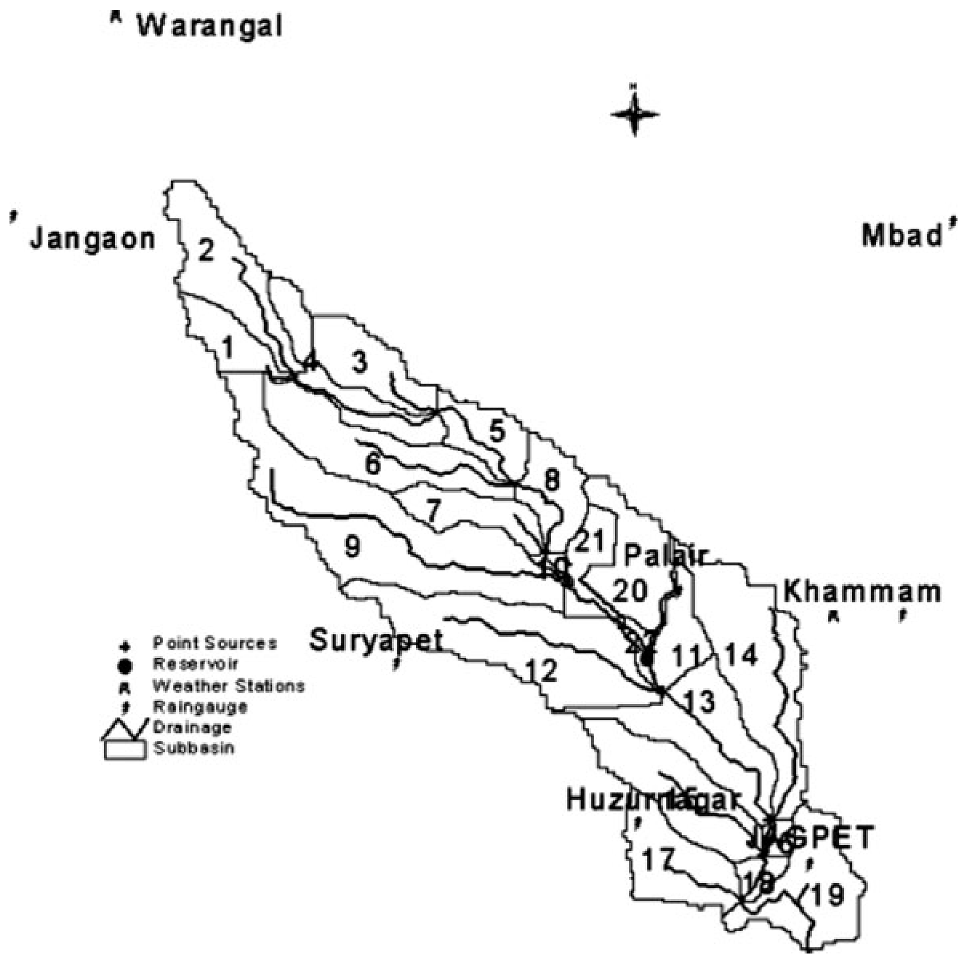

Figure 1. Sub-basin configuration with drainage network of the study area

SWAT model application

Having set up the model, the two major questions that need to be addressed through the modelling study were:

- The quantification of return flow on account of the irrigation brought about in the basin through irrigation projects.
- The estimates of the water yield of the basin when no manmade interference occurred (virgin yield).

In order to answer these questions the following cases have been formulated and the model has been run to get the desired outputs. The model has been run from 1972 to 1994, using daily rainfall data. The first segment of the 'simulation case' is equivalent to the calibration and validation of the model wherein the present conditions have been simulated by mapping all the prevailing activities. No specific calibration has been used, except to adjust the low flow (groundwater) component of the response. This also verifies the capability of SWAT as a model suited for ungauged catchments.

Simulation case—with reservoir in position

This case belongs to the present state, therefore, the Pellaru reservoir has been put in position and imports from the NSLB canal are incorporated. In fact, since the reservoir is a controlled reservoir with known releases into the downstream and imports from the NSLB are being made into sub-basins downstream of the reservoir, it is not essential to model the whole basin. Modelling of only the basin downstream of the reservoir should suffice to answer the first question. The answer to the question of return-flow quantification requires assessment of the utilization on account of irrigation (due to enhanced evapotranspiration). The following simulation runs have been made for the purpose.

Run 1: Incorporating imports from the NSLB canal but without utilizing the same for irrigation (in other words, letting the imports run through the drainage channels).
Run 2: Incorporating imports from the NSLB canal and utilizing the same for irrigation in their respective commands below the reservoir.

The results of the annual yields from the above two runs are given in Table III. The table also depicts the computed utilization on account of a major irrigation project below the reservoir. This utilization has been computed on the basis of the difference in actual evapotranspiration as well as the effect of channel losses. The return flow is then computed by taking the difference between the actual imports and the utilization.

The validation of the simulation can be seen from the comparison of the simulated discharges with the observed discharges at the Palleru Bridge site. The simulation results at monthly interval are given in Figure 2.

Table III. Annual utilization and return flow 1972–1994

Year	Simulated (imports but no irrigation; cumecs-month)	Simulated (imports with irrigation; cumecs-month)	Utilization on account of irrigation (cumecs-month)	Actual imports (cumecs-month)	Return flow	
					cumecs-month	% of imports
1972	1·7800					
1973	6·4630	No imports during this period				
1974	10·0300					
1975	20·9000					
1976	11·9000	10·9200	0·9800	3·083	2·103	68·21
1977	14·8400	11·8900	2·9500	9·250	6·300	68·11
1978	41·6300	35·0400	6·5900	16·963	10·373	61·15
1979	14·9100	11·2700	3·6400	9·255	5·615	60·67
1980	17·3100	7·7230	9·5870	18·510	8·923	48·21
1981	14·9500	9·2050	5·7450	10·798	5·053	46·80
1982	12·2800	7·7740	4·5060	9·255	4·749	51·31
1983	31·2200	24·8600	6·3600	12·340	5·980	48·46
1984	16·4600	10·5600	5·9000	12·340	6·440	52·19
1985	22·3200	14·7100	7·6100	15·662	8·052	51·41
1986	11·3400	4·0420	7·2980	13·188	5·890	44·66
1987	17·3800	11·4500	5·9300	16·565	10·635	64·20
1988	41·5400	34·5100	7·0300	18·138	11·108	61·24
1989	46·0600	38·3300	7·7300	19·154	11·424	59·64
1990	27·4600	21·5500	5·9100	17·986	12·076	67·14
1991	25·0500	18·7200	6·3300	16·904	10·574	62·55
1992	13·4500	9·2080	4·2420	13·608	9·366	68·83
1993	14·6400	8·8920	5·7480	15·838	10·090	63·71
1994	15·8700	10·3500	5·5200	14·495	8·975	61·92

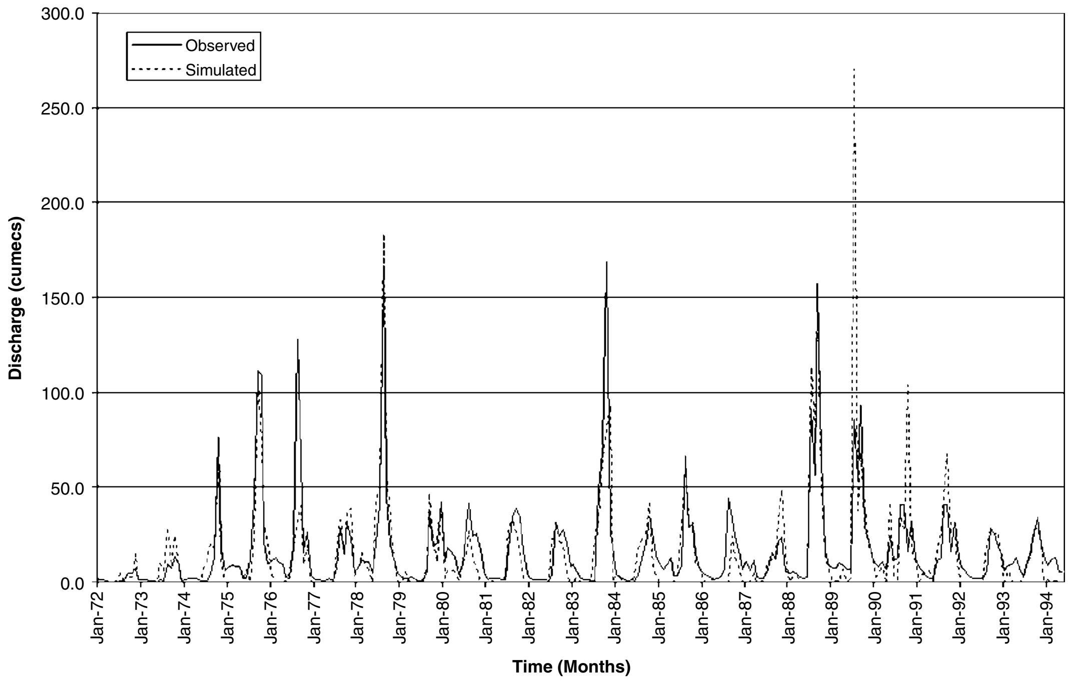

Figure 2. Simulation results at a monthly interval

There have been some years when the observed flows at the bridge site have been proved to be doubtful, since the definite releases have been found to be observed at the reservoir spillway, but the corresponding flows have not been realized at the bridge site.

One such case is that of year 1989. The scatter diagram between the observed and simulated flows at monthly intervals after discarding three such known monthly discrepancies is given in Figure 3.

The scatter diagram for the simulation from 1972 to 1994 gives an R^2 (regression coefficient) value of 0·61 which improves drastically to 0·84 after removing outliers. The goodness-of-fit of the simulations to the observed flows (after removing outliers) for some additional criteria, namely, root mean square error (RMSE), percent bias (PBIAS) and Nash–Sutcliffe coefficient (NS) is shown in Table IV, along with the equations.

Virgin yield

In order to compute the virgin water yield of the Palleru basin, the following two cases have been formulated and run with the parameters obtained with the simulation run.

Virgin case—no irrigation. In this case it is assumed that the crops are rain-fed. The existing ponds/tanks are assumed to be prevailing as invariably they are natural depressions, which have been there for a long time. The reservoir is not in position and no imports are available from the NSLB canal. The results of the annual yield obtained from this run are given in Table V.

Virgin case—irrigation from tanks. The only difference in this case from the previous one is that the water available in the tanks/ponds has been used for growing local crops in the vicinity of these water bodies. This treatment has been applied to the crops grown above the reservoir only because the majority of these tanks/ponds are available in this area. The reservoir is again not in position and no imports are available from the NSLB canal. The results of the annual yield obtained from this run are also given in Table V.

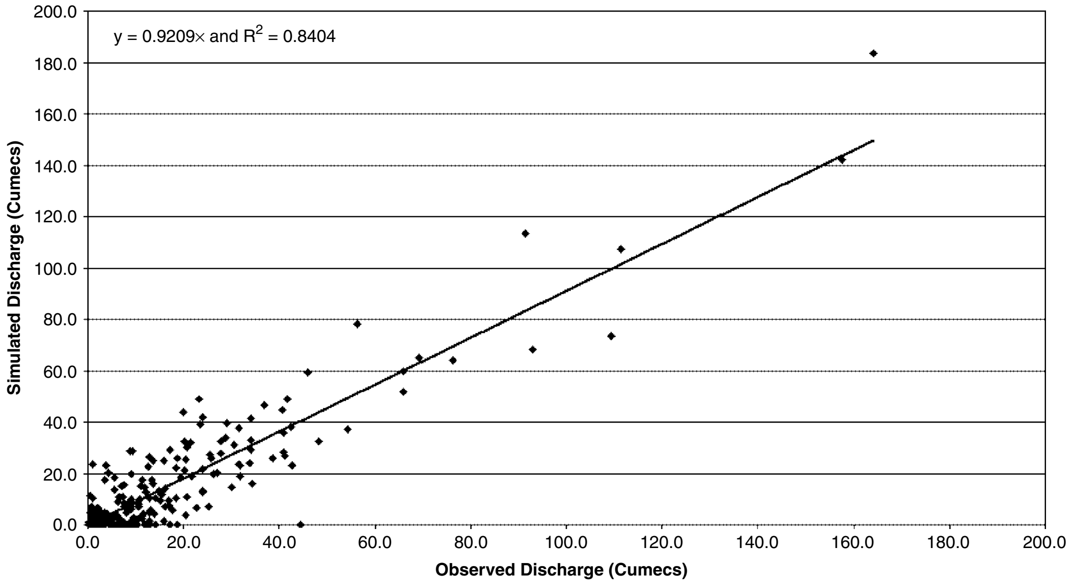

Figure 3. Scatter diagram between the observed and simulated flows at a monthly interval

Table IV. Evaluation of simulation results

Method	Equations	Value
NS (Nash and Sutcliffe, 1970)	$\mathrm{NS} = 1{\cdot}0 - \dfrac{\sum (Y - Y_c)^2}{\sum (Y - \overline{Y})^2}$	0·87
PBIAS (Yapo *et al.*, 1996)	$\mathrm{PBIAS} = \dfrac{\sum (Y - Y_c)}{\sum Y} \times 100$	13·01%
RMSE	$\mathrm{RMSE} = \sqrt{\dfrac{\sum (Y - Y_c)^2}{n - 1}}$	9·18

Y = Observed monthly flow.
Y_c = Simulated monthly flow.
$\overline{Y}$ = Observed mean monthly flow.
N = Number of observations.

Discussion of results and conclusions

This has been a challenging study, where it was required to prove the usefulness of the water balance simulation modelling approach in providing answers to many questions which are not usually possible through conventional approaches being followed presently. The following conclusions have been drawn from the present study:

1. The SWAT model exhibits the capability to simulate complex catchments without much calibration.
2. The results on the utilization and the return flow have been provided through the actual water balance of the area on a daily interval, which in turn is dependent on the climatic and environmental variations observed

Table V. Annual discharge 1972–1994, virgin case

Year	Virgin flow (with rain-fed cultivation; cumecs-month)	Virgin (with minor irrigation; cumecs-month)
1972	2·2210	2·3070
1973	10·1000	10·0200
1974	15·1600	15·1200
1975	16·6200	16·2300
1976	8·1940	8·2080
1977	10·1500	10·3400
1978	41·6100	41·4300
1979	**6·6610**	6·3800
1980	2·3200	2·1720
1981	8·3770	8·1490
1982	6·9970	7·4030
1983	23·2300	23·1100
1984	10·0200	9·9240
1985	13·7500	13·8300
1986	1·3340	1·3360
1987	9·1270	9·2820
1988	27·0600	26·9400
1989	31·1700	30·9200
1990	13·7600	13·4700
1991	13·9900	14·0000
1992	3·3780	3·3250
1993	3·9220	3·7430
1994	6·7350	6·9930
75% dependable $flow = 6{\cdot}66$ cumecs-month		

in the basin. The authenticity of the computed utilizations and return flows obtained through the simulation is indirectly verified with respect to the reproduction of the flows at the bridge site.

3. The return flows of over 50% are appreciably different from the usual rule-of-thumb of 10–20% of irrigation application, used in the country. This revelation can be vital, and useful in proper planning and decision-making.
4. The computation of the virgin yield is also authentic, since it is again based on the actual daily water balance approach through the process-based model and therefore it incorporates the dynamic nature prevalent in all the natural processes.

It may be concluded that such simulation frameworks are essential for integrated river basin planning and management. These frameworks, while dependent on process-based simulation, can also be used to generate various scenarios and check the sustainability of water resources development alternatives.

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